

## Research Article

# SAT: A Software for Assessing the Risk of Desertification in Spain

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Desertification is a major global environmental issue exacerbated by climate change. Strategies to combat desertification include prevention which seeks to reverse the process before the system reaches the stable desertified state. One of these initiatives is to implement early warning tools. This paper presents SAT (the Spanish acronym for Early Warning System), a decision support system (DSS), for assessing the risk of desertification in Spain, where 20% of the land has already been desertified and 1% is in active degradation. SAT relies on three versions of a Generic Desertification Model (GDM) that integrates economics and ecology under the predator-prey paradigm. The models have been programmed using Vensim, a type of software used to build and simulate System Dynamics (SD) models. Through Visual Basic programming, these models are operated from the Excel environment. In addition to the basic simulation exercises, specially designed tools have been coupled to assess the risk of desertification and determine the ranking of the most influential factors of the process. The users targeted by SAT are government land-use planners as well as desertification experts. SAT tool is implemented for five case studies, each one of them representing a desertification syndrome identified in Spain. Given the general nature of the tool and the fact that all United Nations Convention to Combat Desertification (UNCCD) signatory countries are committed to developing their National Plans to Combat Desertification (NPCD), SAT could be exported to regions threatened by desertification and expanded to cover more case studies.

## 1. Introduction

Desertification is defined as land degradation (i.e., reduction or loss of the biological or economic productivity of the land) in drylands (i.e., arid, semiarid, and dry subhumid areas) resulting from various factors, “including climatic variations and human activities” [1]. The magnitude of desertification, which was the first major environmental issue to be recognized as occurring on a global scale [2], was significant enough to set the United Nations Convention to Combat Desertification (UNCCD), a degree of importance only achieved by the Conventions on Biodiversity and Climate Change.

Drylands occupy 47% of the terrestrial surface [3] and are home to over 38% of the world human population [4]. Furthermore, 90% of the human settlements in drylands are located in developing countries [5]. It is valued that severe ecosystem degradation is present in 10–20% of drylands, and its consequences are estimated to affect around 250 million people in the developing world [6]. Progression of desertification worldwide is expected, as deduced from the increased rainfall variability, frequency of droughts, and persistent dry conditions foreseen by the future climate change scenarios [7].

Desertification has been recognized as one of the biggest problems facing the European Mediterranean countries [8, 9]. UNCCD reserves Annex IV to cope with the special

features of the region. Two differing mechanisms can trigger desertification, both associated with the decoupling of natural resource provision and use [10]. The most common has to do with the overexploitation of natural resources, while the second, limited to the European case, is related to rural abandonment [11]. These opposing forces operate simultaneously and allow us to see that the issue of desertification requires a very fine adjustment in the intensity of land use. The challenge is further complicated by climate change. Climate projections predict a 5–30% drop in precipitation in large portions of the drylands in the Mediterranean Basin [12, 13] and an increase in aridity [14].

Strategies to combat desertification include mitigation and prevention. The former are applied when desertification has already deteriorated the territory. The main flagship of these actions is revegetation programmes [15]. They seek to control soil erosion, carbon sequestration, and even the reversal of water imbalances, emphasizing that increasing forest cover raises water yield [16]. The second group of initiatives includes sustainable land management practices [17] or the development of early warning indicators. This last line of action is that addressed in this work, specifically, through the development of computer tools to assess desertification, as the United Nations promote [1].

Early warning indicators seek to detect signals that warn the system is heading towards degradation before it reaches the stable state of “desertification” [18]. Many studies rely on studying the statistical properties of time series in order to detect the proximity of a tipping point or a catastrophic bifurcation point [19, 20]. Different statistical analyses, such as autocorrelation, have emerged in different fields and have been applied to different types of transitions [19]. In addition to studying trends over time, changes in spatial characteristics of the system can provide early warnings of approaching transitions as well [21]. In essence, these indicators seek to detect warn signals that a transition from some initial desired state to a final degraded state is prone to happen. However, our indicators (described in Section 2.2) are of a completely different nature because they are conceived for socioecological systems that are currently undergoing transitions, whose initial states could already be undesired in some senses, and where the question is whether the final equilibrium states will exceed some critical thresholds or not.

Spain is one of the countries most affected by desertification in the Mediterranean region. Drylands occupy 73% of the country. Overall, 20% of the territory is degraded and an additional 1% is actively degrading [22, 23]. Following UNCCD recommendations, the Ministry of Agriculture, Fisheries and Food of Spain (MAFF) implemented the Spanish NPCD in 2008 [24], relying on different methodological approaches for the monitoring and evaluation of desertification.

In order to improve its NPCD, MAFF decided to create an early warning system based on dynamic simulation models. The result is SAT, a computational tool to assess desertification risk in five hot spots. SAT, the Spanish acronym for Early Warning System, is a DSS implemented in Excel that handles SD models performed with Vensim

(Vensim® DSS Version 5.8b) [25]. SAT yields three kinds of outputs: (i) temporal trends of all the variables contained in models, (ii) desertification risk assessment as the percentage of 1,000 simulations in which the values of key variables are above (or below) certain thresholds, and (iii) a ranking of desertification factors according to their impact on key variables.

This paper is structured as follows: Section 2 provides an outline of the simulation models that serve as the basis for the DSS and gives details about the analysis methods implemented to assess desertification. SAT tool is presented in Section 3. Finally, discussion and main conclusions drawn from the study are summarized in Section 4.

## 2. Materials and Methods

*2.1. A Generic Desertification Model.* SD modelling [26, 27] is a methodology that embodies system thinking through the implementation of differential equation systems. SD is interdisciplinary and is grounded in the theory of nonlinear dynamics and feedback control developed in mathematics, physics, and engineering. An SD model consists in a set of ordinary differential equations that makes a stock-and-flow representation of the studied system. SD models are conceived as a structure made up of causal feedback loops including nonlinear relationships and delays.

Agricultural systems and their environmental effects make up complex systems. Their study encompasses socioeconomic variables (demand of raw materials, employment, and land-use allocation), geochemical and ecological processes (aquifer exploitation, soil erosion, and biomass regeneration), and agricultural production techniques (tillage, supplementary feed, and types of crop). To understand the interaction of all these elements, a systemic approach capable of explicitly managing the temporal dimension, sustainability conditions, uncertainty, and externalities is mandatory [28].

The basis of SAT is a GDM [29] that represents the use of resources (soil, water, and pasture) by economic agents (shepherds and farmers) under the predator-prey paradigm [30, 31]. The consideration of human-nature interaction on the basis of this pattern of biological interaction has been successfully adapted to study grazing systems [32, 33]. GDM makes use of this idea and extends it to other land uses. The model highlights the dealings between environmental and socioeconomic variables, clarifies the processes and drivers behind land use and desertification, and copes with the critical gaps of tracking the origins of desertification [34].

GDM is lumped spatially [35] as it does not yield georeferenced results, and its temporal basis is the year. The analysis is focused on desertification syndromes. Their outputs are not designed to fill pixels' data but to spot threatens posed by some land uses. The core of the GDM, outlined in Figure 1, can be described succinctly as follows: the level of resources depends on their renewal and consumption rates. The former relies on the current stock of natural resources, the physical framework (climate and soil type), and a limiting factor, the dynamics of which can be affected by the stock of resources. In fact, soil erosion, soil

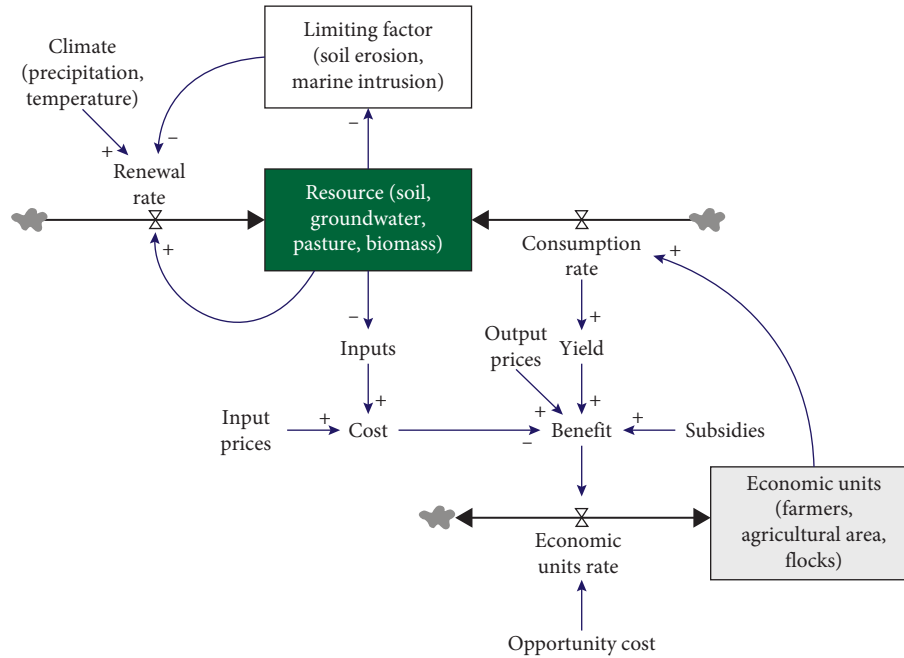


FIGURE 1: General overview of GDM.

salinization, saltwater intrusion, and others have an inhibitory effect on resource regeneration that can be irreversible once critical thresholds are exceeded [36].

Consumption is linked to the number of economic units in the area. They are understood as the number of farmers who make decisions on the size of herds or areas under cultivation. Decisions depend on their benefits compared to the alternative profit, i.e., the opportunity cost of farmers [37, 38]. When, on average, the ratio is above the unit, economic agents intensify their activity by increasing the number of livestock or the agricultural area; the opposite is also true.

Profit increases with income, which depends on yield, production prices, and subsidies. The costs, which penalize the benefit, respond to the use of additional inputs needed for production (supplementary feed, fertilizers, pesticides, fuel, etc.) and their price. Note that the amount of inputs required is conditioned by the stock of natural resources. For example, water table plummeting increases groundwater pumping costs, while the loss of soil and/or biomass drives up the costs of supplementary livestock feed.

Therefore, the deterioration of natural resources has a negative impact on economic activity that should slow down the overexploitation of resources. However, the signs of scarcity fade in an economic context in which certain circumstances (favourable prices, subsidies, technological improvements, etc.) generate the certainty—through indicators based on the profitability of the activity—that those good decisions are being made. For example, if the demand of some crop is very high, its market price can be high enough for revenues to offset or even exceed the rising of pumping costs.

The main output of an SD model is the time trajectories produced from numerical scenarios that capture the initial conditions of the system, i.e., the state in which the model is

started, the values of the form parameters, and the hypotheses established by the user. The simulation period for GDM is set at 200 years, an appropriate time horizon when studying desertification. Indeed, environmental degradation only emerges when we observe the evolution of “slow variables” [6].

Time trends, despite their quantitative accuracy, should not be considered as forecasts. In this sense, it is important to take the nature of the laws underlying the model equations into account. Since they belong to the socio-ecological sphere, i.e., they are not strictly based on physical laws, it is more rigorous to speak of exploration than of prediction [39]. Hence, GDM is intended to be a “means of exploration” [40] for a better understanding of how systems may behave. In this context, the importance of simulation relies in the relative results yielded under different scenarios.

**2.2. Assessing Desertification Risk.** Ultimately, GDM is a state and transition model [41] that uses box-and-arrow diagrams accompanied by data-driven narratives to describe the states of key variables, i.e., the stock of resources and economic units. These models address both reversible and irreversible changes, the details of which are fundamental to understanding desertification and communicating it effectively. This approach requires the establishment of a state called “desertified” with respect to another “non-desertified” or historical/referential state [42].

The desertification risk assessment is carried out within the framework of this dichotomy. The analysis calculates the long-term equilibrium of key variables given current conditions. In this way, it attempts to know the effects of current land-use policies on the system, acting as an early warning

system. Therefore, there are two types of time trends. Those corresponding to stable behaviours are labelled as sustainable and those showing extinction of the resource or some other socioeconomic magnitude are considered desertification (Figure 2).

In particular, the risk of desertification is associated with the probability of losing a critical amount of a key resource within a time frame set by the user. To this end, a thousand simulations are carried out using randomly generated scenarios. Specifically, the `RANDOM_NORMAL` command from Vensim has been implemented. This returns a random number that is different on each successive time step. This algorithm considers a normal distribution of the parameter; in this analysis, some parameters of the scenario are converted into random variables with a mean value and a standard deviation that allows associating a normal distribution to it. For example, when random values of precipitation are used to assess risk, 1,000 precipitation scenarios are generated where values close to the average value of precipitation are more likely to appear than extreme values. After implementing scenarios of different random variables such as subsidies, prices, or the mentioned precipitation, the response of the system is analysed. The final value of the key variables is used to assess the risk of desertification. This indicator is defined as the percentage of simulations in which key resources are exhausted or critical thresholds are surpassed. In addition, it records the number of years required to lose that critical amount of resources.

**2.3. Ranking of Desertification Factors.** Sensitivity Analysis (SA) transcends the validation/calibration stage of a model. It is also a robust technique for obtaining information about a system. The objective is to classify factors (i.e., parameters) and distinguish orders of magnitude from their influences on system behaviour. Specifically, the Plackett–Burman Sensitivity Analysis [43] was performed. This is a sound statistical procedure that measures the effects of each parameter on the target variables in an efficient way in terms of the number of necessary scenarios. An important feature is that the effects of every parameter are not measured with the all-other-things-being-equal assumption but are averaged over variations made in all other parameters. PBSA also enables measuring two-way interactions of pairs of parameters, although this option has not been used in this case.

To apply PBSA, upper and lower values (10% for this evaluation) must first be assigned to each parameter in the model. The next step is to design  $2d$  scenarios, where  $d$  is any multiple of 4 greater than the number of  $n$  parameters. Each scenario is a set of  $n$  parameter values that are sampled from the previously assigned upper and lower values. The design of these scenarios follows the patterns originally proposed by Plackett and Burman [43]. The effects of each parameter are obtained by adding the  $2d$  outputs of the target variable and then dividing it by  $d$ .

The evaluation procedure focuses on tailor-made variables that assess the time needed to lose a key resource. These are “slow” variables, which are appropriate indicators for assessing the system change in the long term [6]. The positive

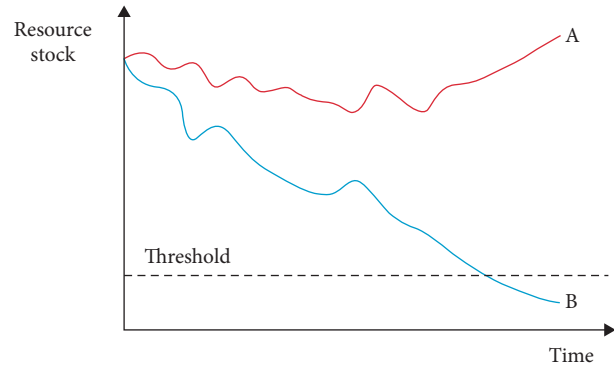


FIGURE 2: Basis for SAT early warning indicators. Some simulations do not exceed the degradation thresholds considered (A), while others do (B). The latter determine the risk of desertification.

sign indicates the fact that incrementing 10%, that parameter value delays degradation while a 10% decrease accelerates degradation. A negative impact should be interpreted in the opposite way.

### 3. Results

SAT was implemented for five case studies (Figure 3), each one of them representing a DL identified in the Spanish NPCD [24]: (DL1) “Woody crops affected by erosion”; (DL2) “Rainfed herbaceous crops with erosion risk”; (DL3) “Overgrazed agroforestry-pastoral systems”; (DL4) “Irrigated areas with desertification risk”; and (DL5) “Degraded shrublands and wastelands.”

The five cases were covered with three versions of GDM previously developed by the authors:

- (i) GDM1 (rangelands): water erosion in rangelands and shrublands [28, 37, 44, 45] for Dehesas in Cáceres province (DL3) and Sierra de Los Filabres in Almería province (DL5)
- (ii) GDM2 (croplands): water erosion in extensive croplands for olive orchards (DL1) and wheat/sunflower crops rotation (DL2) in Córdoba province [46]
- (iii) GDM3 (irrigation agriculture): hydrological models linked to groundwater-based irrigation agriculture [36, 47, 48] for Eastern La Mancha aquifer in Ciudad Real and Albacete provinces apply to DL4

Interaction with simulation models has improved considerably in recent years. However, it can still be difficult for a non-modelling user to deal directly with programs such as Vensim. User-friendly interfaces are essential to involve a broader audience in exploiting and improving models. The Vensim DSS® software [25] includes the possibility of developing simple Venapps applications to visualize the model structure, examine its causality, simulate the model behaviour, and visualize its results.

Alternatively, it is possible to control Vensim through other applications. This was the option chosen, as one of the main requirements in the SAT design was to use a platform to which most users were familiar. SAT is a Vensim



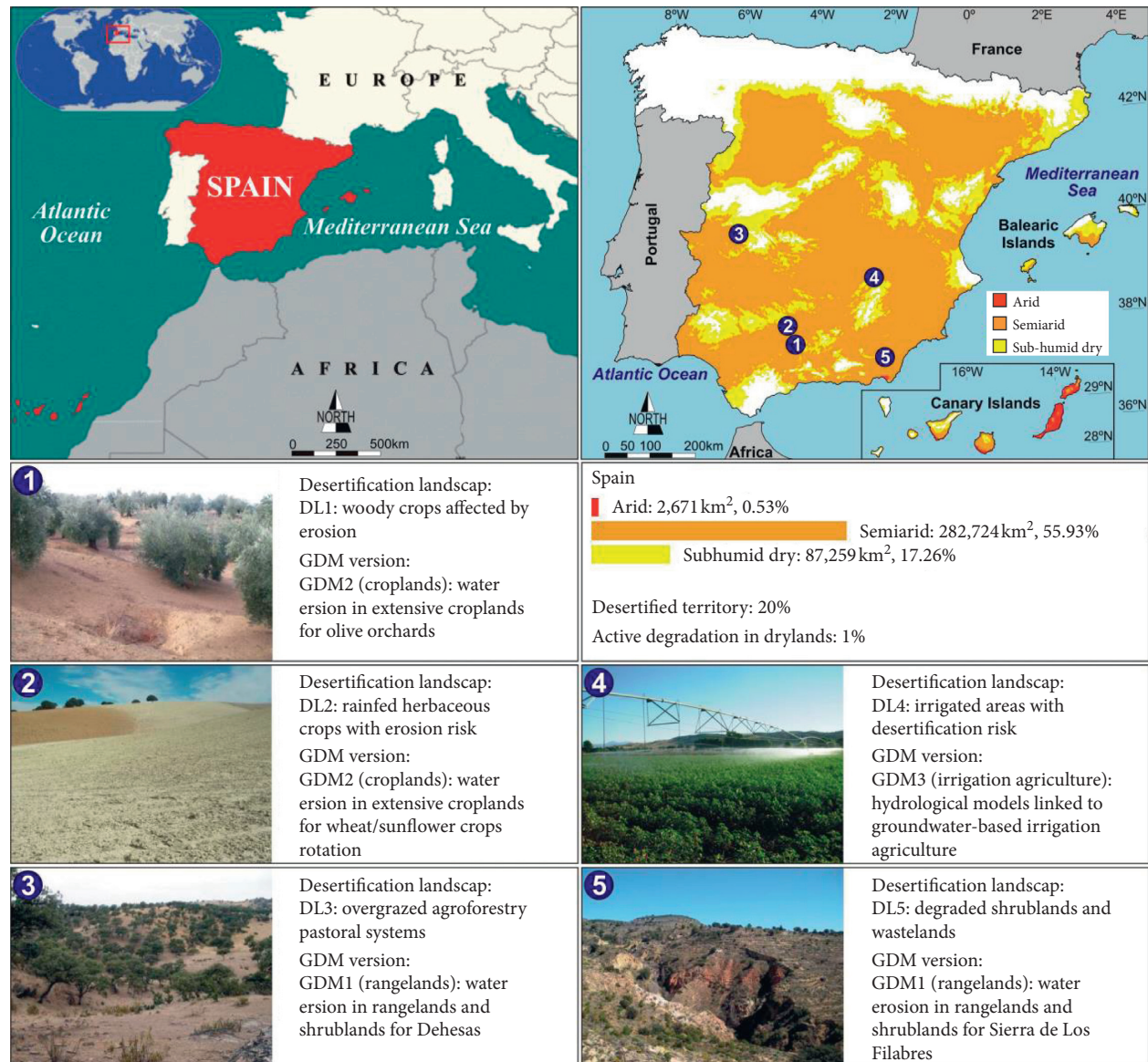


FIGURE 3: Drylands (arid, semiarid, and subhumid dry areas) in Spain and location of the five case studies.

Published Application (vpa) implemented in Excel that is ready to work with Vensim Model Reader (<https://vensim.com/free-download/>). In our case, the vpa consists of a SD model (SAT.vmf) and a caller (SAT.xls), the true user interface. Around these main files, other ones help to manage the model outside the Vensim environment (Figure 4). Table 1 lists all of them, and their interaction is illustrated in Figure 5.

SAT is organized into three blocks (Figure 6 (top)), each of which corresponds to a version of GDM. However, to simplify programming, the three GDM adaptations have been merged into a single Vensim file (SAT.vmf). The Main Menu (Figure 4) is used to go from one case to another and provides general information about the project. The other parts of the Excel book with which the user interacts are the scenarios and results. In each of these spreadsheets, the scenarios are established, the different

indicators are calculated, and the results are presented (Figures 7 and 8).

Beyond the interface elements, there are hidden structures where all calculations and operations are executed (Figure 6 (bottom)). They consist of sheets inside the main workbook (SAT.xls) and external files that are necessary for the operation of the Vensim models. Thus, each version of GDM includes four additional worksheets to organize intermediate calculations and store the results and data used. These are as follows: (i) “s1” and “s2” contain the numerical values of the time trajectories that feed the graph, the “s1” being also used to store the base scenario values; (ii) the “risk” sheet stores and processes the results of the 1,000 simulations needed to assess desertification risk; and (iii) in “pbsa” the scenarios required by PBSA are implemented. In addition, here, the matrix calculations are executed to establish the ranking of the factors of desertification.

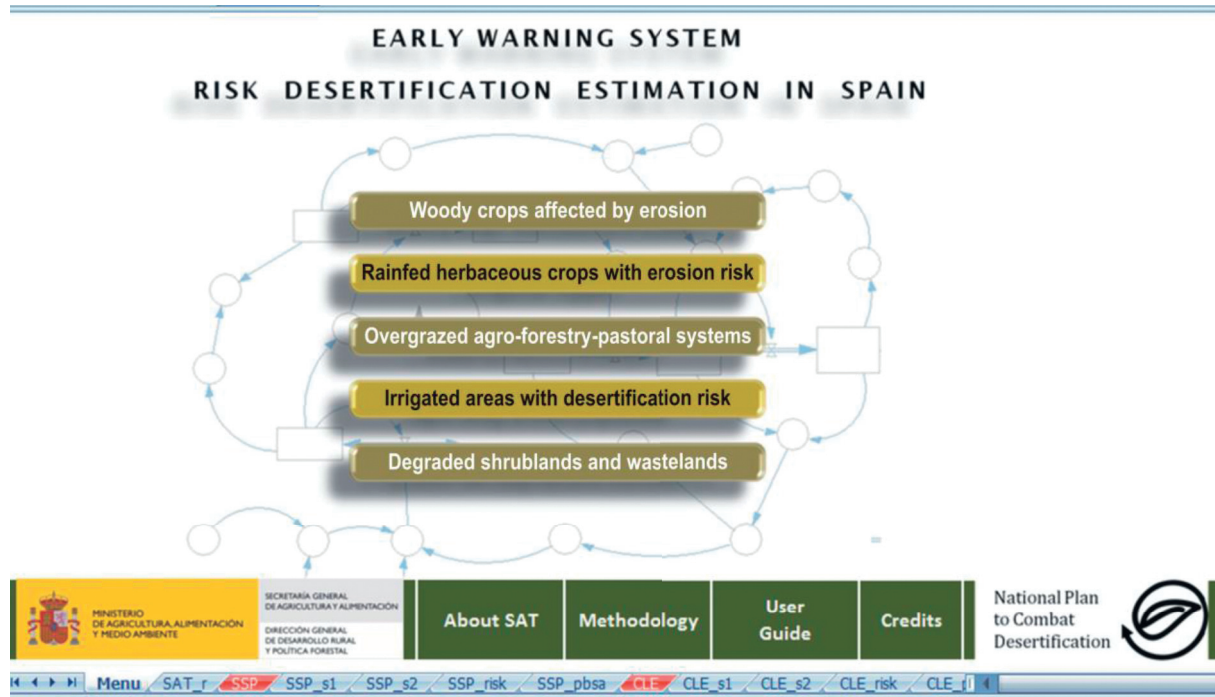


FIGURE 4: SAT Main Menu.

TABLE 1: Files compiled in SAT DSS.

File	Type	Number	Description
SAT.vmf	Vensim simulation model	1	The usual extension of a Vensim model is *.mdl. However, to be compiled, it must be saved in binary format (*.vmf).
SAT.xls	Excel file	1	Contains the user interface and works as a caller for the rest of files.
Results.xls	Excel file, v 4.0	2	Provides the link between Vensim and Excel.
Parameters.xls	Excel file, v 4.0	1	Provides the link between Excel and Vensim.
Name.vdf	Vensim Data file	<i>n</i>	Contains scenario results from a simulation; the name of the exercise is provided by the user.
Parameters.vdf	Vensim Data file	1	Contains data from the scenario of simulation provided through SAT.xls.
List.lst	Vensim list	9	List of model variables to export to Excel.
Read.frm	Vensim input form	1	Specifies how Excel data are read by Vensim.

The additional files to connect the SAT interface with the model are Excel 4.0 files, the format required by Vensim. Finally, at the last level is the simulation model, the real core of the DSS.

The SAT tool is programmed with Visual Basic. A part of this code automates tasks in Excel and another one interacts with Vensim DSS through DLL commands. A dynamic link library (DLL) is a collection of small programs that can be loaded when larger ones need them. Each of these programs is made up of commands, i.e., actions performed by Vensim. They are introduced as a class, followed by the specific command and the options that allow its customization in the form `class > command|option1|option2....`

The command `Vensim_command` is the DLL used in SAT. Actually, a small portion of the available commands is enough to take control of Vensim from Excel. They belong to three classes (Table 2): (1) MENU commands have essentially the same effect as selecting a command from the Vensim workbench menu; (2) SIMULATE class allows

controlling simulation input control parameters and also reads results from other runs to start another simulation; and (3) SPECIAL commands allow manipulating the Vensim environment in similar ways to what can be done from the Control Panel.

Figure 5 illustrates the operation of SAT. In a simple simulation exercise (which generates time trajectories), the loop is started after clicking on the “Trends” button (Figure 7(c)). Then, the *Parameters.xls* file is updated with the parametric values that the user has entered in the scenario. They are automatically converted to *Parameters.vdf*, the Vensim format (vdf denotes Vensim data file). The command used for this operation (MENU > XLS2VDF) involves the file *Read.frm*. It specifies the import options for Vensim to read the Excel file correctly.

Once data files are set to be used in the simulation (SIMULATE > ADDDATA; SIMULATE > DATA), the model is run (MENU > RUN) under a name given by the user (*Name.vdf*) (SIMULATE > RUNNAME). The

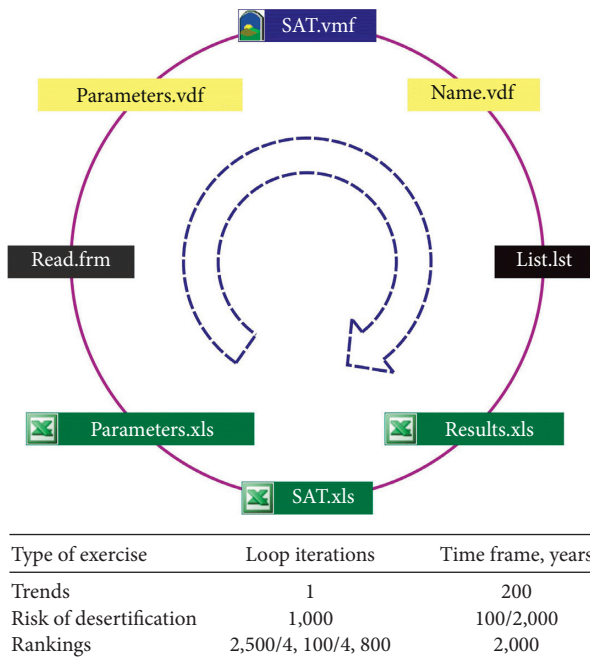


FIGURE 5: SAT basic operation scheme. The table shows the number of iterations and time frame for each of the simulation options.

information generated in each simulation includes values for each variable and for each time step (0.0625 years) for a long simulation period (200 years). However, only a small part of this huge amount of data is used in SAT. The Vensim data file (*Name.vdf*) is converted back to Excel (MENU > VDF2XLS), generating *Results.xls*. The file *List.lst* is used to determine which variables are exported. Finally, the information in this file is updated in *SAT.xls*.

For desertification risk assessment, this loop is repeated 1,000 times. To determine the ranking of factors, the number of simulations ranges from 2,400 to 4,800, since the amount of PBSA scenarios is subjected to the number of parameters of each GDM version. At each turn of the loop, the results of a simulation are saved in *SAT.xls*. Once the exercise is completed, a set of calculations is executed to calculate the indicators that the user finally sees. In addition, they can be saved in \*.txt format for consultation.

When the user opens the application, the first screen that appears is Main Menu (Figure 4). Here the user can find general background information: a user guide, an overview of the implemented methodology, and the software credits. The Main Menu gives access to the five DLs included in SAT. After selection, the worksheet is updated with the corresponding baseline scenarios. The available options include (Figure 7): (a) links to the Main Menu and to the supporting documents on the analysed case; (b) implement new simulation scenarios; (c) possibility of launching three types of simulation exercises; (d) files management; and (e) summary report of the results of the exercises.

The basic two steps for working with SAT are to fill the data in the simulation scenario and then to run any of the three exercises. The scenario can be created by changing the

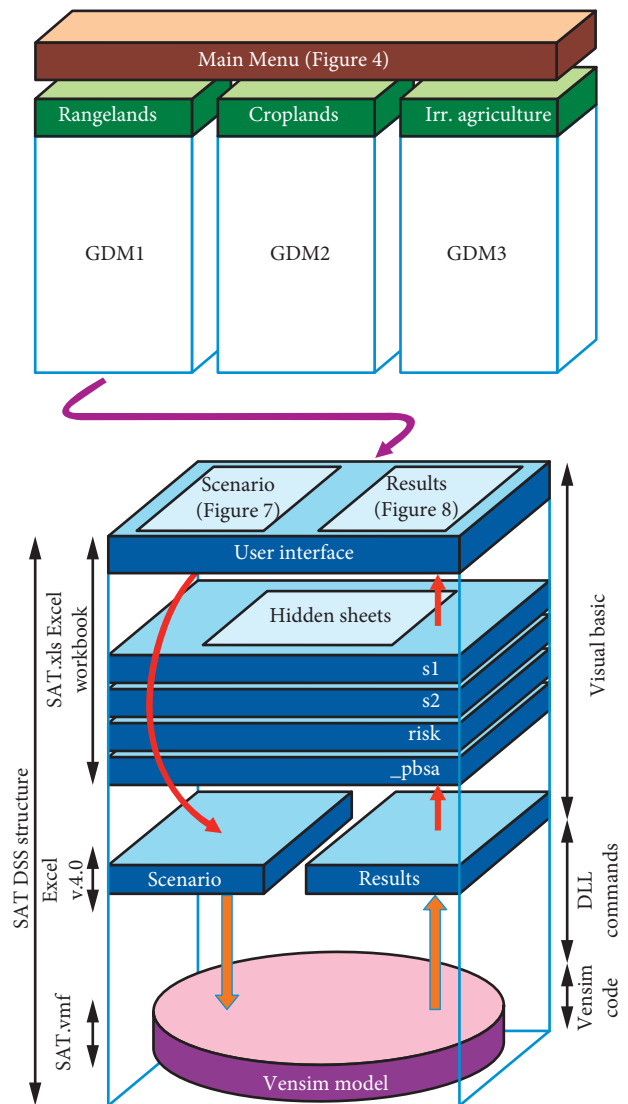


FIGURE 6: Overview of SAT DSS structure (top portion). The five case studies are implemented using only three simulation models. Each of them forms an independent block (accessible from the Main Menu) in which the relevant *SAT.xls* sheets and diverse Excel and Vensim files specific to the version of the GDM used are interconnected (see Figure 5). Detailed arrangement of the files for the Rangeland GDM version is shown (bottom portion).

baseline scenario loaded by default. It is also possible to make use of other scenarios that have been saved previously or create a completely new one by clicking on the “Clear scenario” option.

The “Trends” exercise immediately generates a graph representing the trajectory (red line) of the variable selected in the upper combo box. For comparison, an alternative simulation (blue line) can be loaded.

The other two exercises take longer (see table in Figure 5), as thousands of simulations to calculate desertification indicators and rankings are needed. After a few minutes, the results can be consulted by scrolling down (Figure 8). Together with the simulation scenario, the user has to set the time horizon of the exercise “Risk” in 100 or 2,000 years.



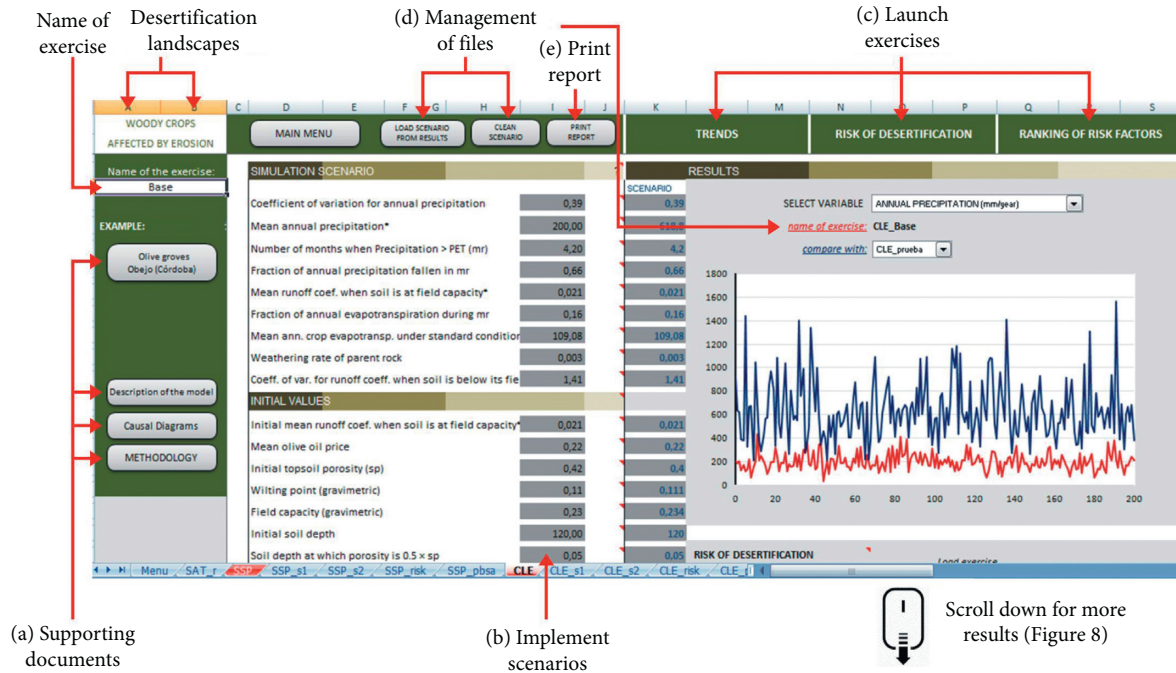


FIGURE 7: Screen for one of the cases implemented in SAT DSS.

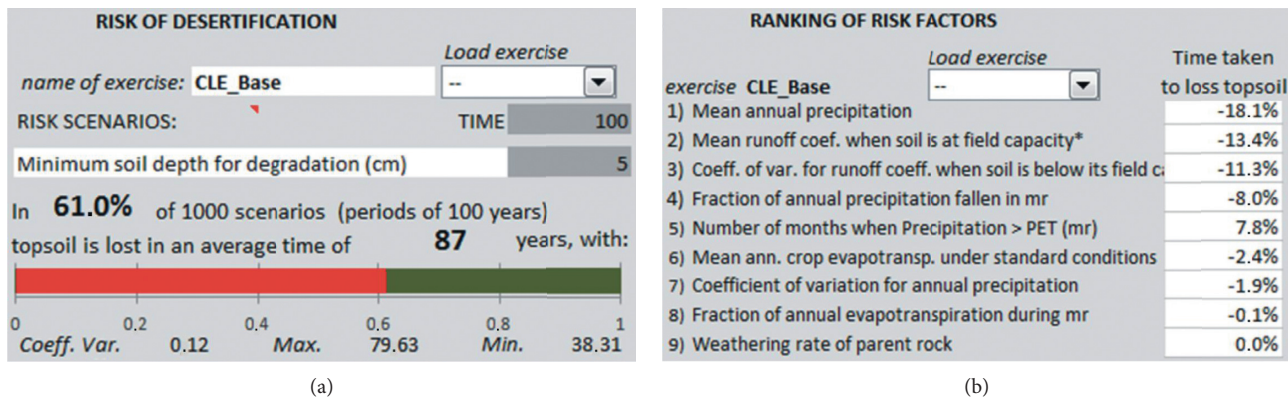


FIGURE 8: Outputs for risk (a) and ranking (b) exercises. Example for landscape DL1 “Woody crops affected by erosion.”

TABLE 2: Vensim commands implemented in SAT.

Command	Function
MENU > XLS2VDF	Converts the Excel format file to the *.vdf format file
MENU > RUN	Runs the model using the current simulation setup
MENU > VDF2XLS	Converts the Vensim dataset to an Excel v. 4.0 format file
SIMULATE > ADDDATA	Adds a *.vdf file to the list of data files to be used in the simulation
SIMULATE > DATA	Sets the data file(s) to be used in the simulation
SIMULATE > RUNNAME	Sets the name of the simulation run
SPECIAL > LOADMODEL	Loads the model

By way of illustration, the results for DL1 are shown in Figure 8(a). They can be interpreted as follows: the risk of soil thickness falling below a critical threshold for productivity (set at 5 cm for the user in this example) is estimated at 61%, and this can occur within 87 years. Together with the main output, a statistic summary (mean, coefficient of variation, max, and min) is included. Finally, Figure 8(b) shows the

classification of the parameters. The results are interpreted as follows: a 10% increase in “mean annual precipitation” means that the “time needed to lose the topsoil layer,” the target variable for this case, increases by 18.1%.

All simulation exercises are saved by default for later use. Trends are saved in \*.vdf format generated by Vensim. From there, both simulation scenarios and results can be retrieved.



TABLE 3: Time for soil collapse under two assessment methodologies.

Case study	“Simple” soil erosion indicator, years	SAT estimation, years	Percentage of variation (%)
DL2	200	26	−87
DL1	657	169	−74
DL5	1,045	186	−82
DL3	1,739	349	−80

From the other two exercises, only the final output, i.e., the desertification risk and the ranking of risk factors, is saved in \*.txt format, but not the thousands of simulations necessary for their calculation.

#### 4. Discussion and Conclusions

Prevention and mitigation of desertification includes understanding its causes, monitoring and evaluating its progression, and designing and implementing site-specific management strategies [18]. Given the irreversible nature of desertification, it is essential to anticipate the problem [22, 49, 50]. SAT is a software aimed at contributing to this problematic of the fight against desertification. The mere fact of constructing a SD model that allows the understanding of the physical and socioeconomic processes involved is a great advance to propose sustainable solutions. Furthermore, by coupling numerical methods such as SA or probability calculations, we achieve an objective assessment of the risk of desertification and of the most important factors.

Our early warning system complements the indicators that the Spanish NPCD [24] already had. These were based on the methodology of MEDALUS [51], a widely known technique for assessing desertification in the Mediterranean area. This provided a qualitative evaluation of the risk of desertification of the territory by analysing each pixel from basic information that was readily available (estimated erosion, aridity index, aquifer overexploitation, and recurrence of forest fires). Its weakness has been highlighted in the latest World Atlas of Desertification [52]. The main criticism of this approach is that land degradation cannot be mapped by a single indicator or by any arithmetic or modelled combination of variables [53]. In addition, the dynamics of the processes are ignored, the importance of which can be illustrated by the following example. Table 3 shows the time for soil loss in the case studies included in SAT under two methodological approaches: (i) a “simple” indicator (second column) estimates soil loss by dividing the soil thickness by the average annual rate of erosion (previously converted from tons/ha to mm through soil bulk density) and (ii) SAT procedure (third column). The percentage of variation relative to the “simple” indicator appears in the last column.

It is noted that the degradation times for the “simple” indicator are much longer than the SAT results. The reason is due to the static nature of the above indicators. In fact, the assumption of a constant erosion rate, which implicitly incorporates the “simple” indicator, is not supported from a medium-to-long-term perspective. This consideration is essential for desertification, as this process is governed by “slow variables” [6]. By way of illustration, erosion rates may change due to fluctuations in vegetation cover—the

literature describes the exponential nature of this relationship [54]—driven by livestock density which, in turn, is sensitive to price changes in livestock markets [55].

In fact, the differences observed between the two types of indicators are the result of considering positive feedback in the soil loss process. Soil erosion exposes layers of higher apparent density, i.e., deep layers having lower porosity and lower infiltration rates. Soil crusting prevents seeds from sprouting and reduces water entry into the soil. This, in turn, increases runoff rates and soil erosion. All these mechanisms are ignored by the “simple” indicators, which consider soil loss as a linear process.

There are also clear limitations in the case of groundwater-based irrigation agriculture. It could be said that the sustainable groundwater use implies that the aquifer piezometric level is steady. However, the shift from a steady state (aquifer under natural regime) to the other state (aquifer under sustainable use) implies that the recharge-to-discharge ratio turns less than one for the period in which the disturbance (the development of irrigation agriculture) remains. Hence, just like the use of average constant erosion rates, the implementation of constant recharge-to-discharge indicators ignores the dynamics (feedbacks and delays) of the groundwater resource. Actually, a less-than-one ratio is a necessary, though not sufficient, condition to declare groundwater overexploitation [56, 57]. Some key questions arise as follows: What is the expected trend for irrigation areas? Is it possible that the recharge-to-discharge ratio returns to one? How long can it take? What would be the stock of groundwater at the time? It is impossible to get an idea of the answers to these questions without taking into account the set of dynamic processes—at least the most important ones—involved in the use of the groundwater resource.

Monitoring indicators over time helps to overcome their static disadvantage. The inherent problem with indicators based on “flash” observations or remote sensing techniques is that they show the current, actual state of the system. This merit becomes a disadvantage when it comes to inertial systems. When irreversible thresholds and delays are part of the system [19, 27, 58], it is imperative to have an idea of the general trend of the system before the symptoms of desertification become so evident. Otherwise, monitoring results in a kind of necropsy that records the path to collapse.

The users targeted by SAT are government land-use planners as well as desertification experts. The former are in charge of updating the NPCD, and SAT will provide them with land use trends under different scenarios and their associated desertification risk. The latter will contribute their knowledge and data to improve process modelling and to refine thresholds and parametric values.

The growing perception of the complex interaction between the sociocultural, economic, and biophysical components of systems is the cause of the growing interest in environmental DSSs [59, 60]. Such platforms play a key role in the expansion of research results to society. They allow, in an easy way, to explore modelling and its results and introduce their users to the decision-making process [61]. In addition, they diminish the resilience of society in dealing with the problems of desertification [18].

DSS should work in two ways: first, by bringing scientific research closer to social agents. Thus, when the decision-making process and the premises on which it is based are opened to public debate, there is a gain in transparency [62]. Second, this approach can be useful for researchers. In fact, the participation of non-scientific stakeholders and experts raises interesting questions as they reflect society's main environmental concerns.

On SAT, one of the main tasks of stakeholders and experts was to agree on degradation thresholds. There were some difficulties in interpreting the results and defining the scenarios, as some of the parameters were difficult to understand. This is part of the communication barriers between scientific research and the real world, and as in [59], "there is a trade-off between the attempt to simplify the intrinsic complexity and the need for scientifically robust approaches and detailed high-quality data."

An important conclusion after SAT is the need to model the land-use change (LUC) [42], as these are the main drivers of global environmental change [63, 64]. Model development for particular land uses provides a limited perspective on the causes and consequences of desertification [6, 65]. We agree with the demand to develop models that cover various land uses in an increasingly interconnected world (e.g., landless livestock trigger soybean cultivation). However, GDM and SAT were conceived under the umbrella of DLs linked to specific land-uses, nourished by the *hotspot* concept, i.e., a sudden increase of economic productivity driven by the intensification and expansion of a certain land-use. What is more, GDM implicitly considers the most important form of land conversion, which is the encroachment of arable and grazing lands on natural ecosystems [63].

This reason encourages us to include more case studies in SAT. In addition, specific land-use modelling is a preliminary step for its integration into the LUC framework. Increasing the collection of models will give us a precise idea of the desertification risk state in Spain. Even more, the computational system is ready to be exported to other countries. GDM has been already adapted to study groundwater-dependent oases in Morocco [56]; Alcalá et al. [66, 48], Greek rangelands [37], and Algerian steppe rangelands [50]. Given that all the UNCCD signatory countries are committed to develop their NPCDs, this kind of tools can help threatened regions to spot desertification processes in their initial stages.

Under the increasing climatic and social uncertainties enveloping the entire planet, SAT pursues—to quote Abraham Lincoln—not only to know where we are but also to sketch where we are trending. In that case, we could better judge what to do and how to do it.

## Abbreviations

DL:	Desertification landscape
DLL:	Dynamic link library
DSS:	Decision support system
GDM:	Generic desertification model
LUC:	Land-use change
MAFF:	Ministry of Agriculture, Fisheries, and Food of Spain
NPCD:	National Plan to Combat Desertification
PBSA:	Plackett–Burman sensitivity analysis
SA:	Sensitivity analysis
SAT:	Sistema de Alerta Temprana (early warning system)
SD:	System dynamics
UNCCD:	United Nations Convention to Combat Desertification.

## Data Availability

The data used to support the findings of this study are available from the corresponding author upon request.

## Conflicts of Interest

The authors declare that there are no conflicts of interest regarding the publication of this paper.

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